91602
new 82-10

ontario hydro
research division

DR. D. MILLS
Director of Research

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

ELECTROSTATIC PRECIPITATION OF DUST RESULTING FROM THE COMBUSTION OF COAL IN POWER PLANTS FITTED WITH DRY SO_2 CONTROLS - A LITERATURE REVIEW AND PRELIMINARY ASSESSMENT

ABSTRACT

Electrostatic precipitators (ESPs) currently in use at coal-fired generating stations were designed to collect flyash alone. Proposed methods of dry SO_2 reduction through the addition of lime or limestone ahead of the precipitators will produce large amounts of high resistivity flyash/sorbent particulate matter, and it is anticipated that modifications to the ESP will be required to meet emissions limits. This paper reviews the operation of electrostatic precipitators and outlines various measures that have been proposed for upgrading ESP performance.

1.0 INTRODUCTION

Electrostatic precipitators (ESPs) are commonly used for the control of flyash emissions from coal-fired generating stations. Some of the acid gas controls being considered by Ontario Hydro will result in particulate emissions of a different chemical nature and in significantly increased volumes than the flyash currently being produced. It is generally believed that the performance of the existing ESPs will not be sufficient once the SO_2 reduction strategies are implemented, and upgrading of the particulate control equipment will be required.

This paper reviews the basic mechanism of ESP operation, the effect of various operating parameters on ESP performance and describes some of the methods that have been proposed in the recent literature to upgrade their performance.

job	file	date	report no.
35-528-091	837.2413	August 5, 1987	87-199-K

2.0 PRECIPITATOR OPERATION

In a standard wire-plate precipitator, the incoming dust-laden gas flows between negatively charged wire discharge electrodes and grounded plate collecting electrodes. When the voltage gradient is sufficiently great (about 3000 kV/m in ambient air) electrical breakdown of the gas occurs and ionized molecules form from the uv radiation of the corona glow discharge (Strauss, 1975). These molecules accelerate towards the negative conductor and release electrons from the conductor surface. These, in turn, generate more positive ions and electrons on impact with gas molecules. Electrons swarm outside the corona region, moving with less speed than is required for ionization. These electrons attach themselves to gas molecules, forming ions, which travel towards the collection plates with a speed proportional to their charge and to the intensity of the electric field. Ions collide with, and adhere to, particles in the gas causing them to be electrically charged and to migrate towards the collecting plates. This process is illustrated in Figure 1.

2.1 Field Strength and Corona Current

The field strength, E, is the potential gradient at any point between the +ve and -ve electrode (V/m). For corona formation, electrical breakdown of the gas must occur at the surface of the discharge electrode. The critical field strength for the onset of corona discharge can be found from Peek's semi-empirical correlation:

$$E_c = 3 \times 10^6 \, m\left(\frac{T_o P}{P_o T} + 3.0\sqrt{\frac{T_o P}{P_o T R_1}}\right) \qquad (1)$$

where m = wire roughness factor (m < 1 for rough wires)

R_1 = wire radius,

P = pressure in atm,

P_a = 1 atm,

T = temperature in K,

To = 298 K.

Thus the thickness of the discharge wire has an effect on the corona starting voltage. As the diameter of the wire decreases the electric field near the wire increases, but the magnitude of the field drops off rapidly with distance from the electrode surface. With larger wires, the field strength at the electrode is lower but the gradient is also less (Oglesby and Nichols, 1978).

FIGURE 1

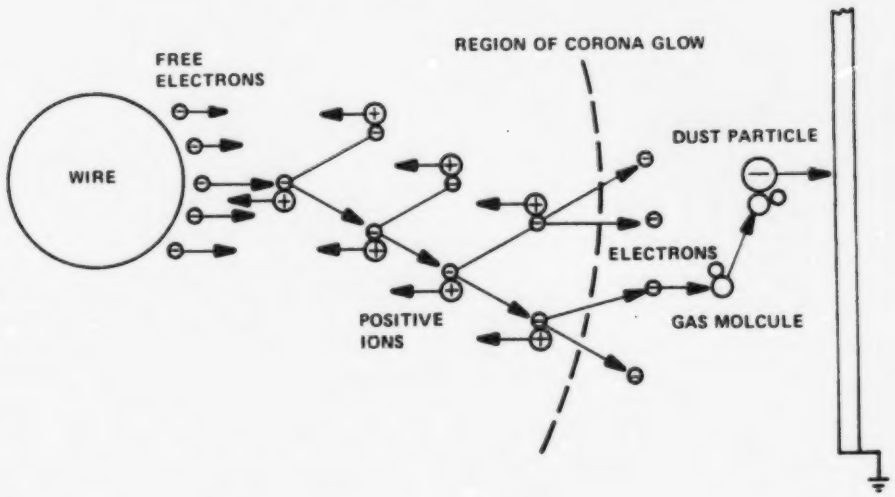

ILLUSTRATION OF THE CORONA GENERATION PROCESS
FROM OGLESBY AND NICHOLS, 1978

After the corona is started, the field strength has been found experimentally to be given by

$$E = \sqrt{\frac{8iL}{u_i W}} \qquad (2)$$

where L = distance from wire to plate,

W = distance between wires,

i = ionic (corona) current per unit length of conductor, A/m,

u_i = ionic mobility in a unit field, $m^2/(sV)$.

To maintain a stable negative corona, it is necessary that a sufficient space charge, σ, exist in the interelectrode space. If the space charge is too low, the avalanche process grows until sparking occurs between the wire and plate. The space charge builds up as gas molecules collect the free electrons generated in the corona region. The total space charge has three components; that due to the electrons, the negative ions and the dust particles. The mobility of electrons, however, is so great that they pass through the interelectrode space very quickly and make a very small contribution to the total space charge. As the dust-laden gas passes through the precipitator, particles are removed, and the space charge decreases. Thus, the current density of the precipitator outlet field is higher than that of the inlet field (Oglesby and Nichols, 1978).

When particulate matter is present the electric field can be found using:

$$E = \left(1 + \frac{\varepsilon S r}{\varepsilon + 2}\right) \sqrt{\frac{8\ i\ L}{u_i\ \ W}} \qquad (3)$$

where ε = dielectric constant of the particles,

S = total surface area of particles per unit gas volume,

r = distance from discharge electrode.

The corona current is a function of the applied voltage, the ion mobility and the precipitator dimensions.

2.2 Particle Charging

There are two mechanisms of particle charging that occur simultaneously. The electrons and gas ions travel across the gas stream, charging particles with which they collide. This is known as bombardment charging. Diffusion charging occurs when gas ions and electrons land on particles due to collision resulting from thermal motion. The first mechanism is more

important for particles greater than 1 μm in diameter and the second is more important for particles less than 0.2 μm in diameter. Charging by ion bombardment is the most effective mechanism for charging particles but the selectivity is practically zero.

The charge on a particle (q, coulombs) is a product of the electronic charge, e, and the number of these charges, n.

$$q = ne = \frac{3\varepsilon}{\varepsilon+2} \frac{d^2}{4} \frac{E\ t}{t+\tau} \qquad (4)$$

where t = time of charging,

τ = time constant = $1/(\pi\ N_i e\ u_i)$,

N_i = ion concentration per unit volume.

As $t/\tau \longrightarrow \infty$, the limiting charge on a particle can be calculated from:

$$q = \frac{3\varepsilon}{\varepsilon+2} \frac{d^2}{4} E \qquad (5)$$

in which the dielectric term varies from 1 for a vacuum to 3 for perfect conductors. On a conductor, this charge is redistributed almost instantly, whereas on a non-conductor, the redistribution is very slow. Diffusion charging and field charging occur simultaneously and both are important for particles in the 0.1 to 1.0 μm range. At low field intensities, diffusional charging dominates and at high fields, charging by ion bombardment is more significant.

2.3 Particle Drift

Particles move towards the collecting plate with a migration velocity, w, under a force F, given by F = qE and the opposing drag force given by

$$F' = \frac{C_D}{C} A \frac{1}{2} \rho w^2 \qquad (6)$$

where C_D = drag coefficient,

C = Cunningham correction factor,

A = projected area of the particle,

ρ = particle density.

Assuming that the particles are fully charged, spherical, and in Stokes law flow, the migration velocity can be calculated using equations 7 or 8:

$$w = \frac{\varepsilon\ C\ E^2\ d}{(\varepsilon+2)\ 4\pi\mu} \qquad (7)$$

This velocity can vary by a factor of 3, depending on the dielectric constant of the particulate material, and is directly proportional to the particle diameter and inversely proportional to the gas viscosity. In S.I. units the expression for the migration velocity is

$$w = \frac{2\varepsilon_a}{\mu} CE^2 d \qquad (8)$$

where ε_a is the permittivity of free space = 8.86×10^{-12} farad/metre.

2.4 Collection Efficiency

Efficiency is an exponential function of the gas stream residence time in the precipitation field. The Deutsch equation is used to predict the collection efficiency of an electrostatic precipitator.

$$\eta = 1 - \exp\left(\frac{-wA}{Q}\right) = 1 - \exp\left(\frac{-wt}{L}\right) \qquad (9)$$

where A = total collection area,

Q = volumetric gas flow rate,

t = gas residence time.

In practice, the apparent migration velocity, w, is a dimensioning constant, the efficiency, plate area and gas flow rate are known and w can be calculated. Since larger particles have greater migration velocities than smaller particles, the calculated effective migration velocity decreases as the precipitator efficiency for small particles increases. The various size fractions of dust should properly be treated separately.

In order to "flatten" the effective migration velocity vs efficiency curve, the Deutsch equation can be modified (Matts, 1986) to

$$\eta = 1 - \exp\left(\frac{-w_k t}{L}\right)^k \qquad (10)$$

with k = 0.5 giving a relatively horizontal curve for many installations. Thus w_k is a constant that takes into consideration the heterogeneous nature of the dust. However, w_k increases with L, the spacing between the charging and discharging electrodes. The ratio w_k/L gives a generalized time constant of electrostatic precipitation (given the symbol M_k) so that

$$\eta = 1-\exp(-M_k t)^k \qquad (11)$$

Cooperman (1984) presents a more rigorous efficiency theory, of which the Deutsch equation is a limiting case.

2.5 Precipitator Geometry

2.5.1 Corona Electrode Diameter

Large discharge electrodes require higher corona starting voltages and produce steeper current voltage curves than smaller electrodes. A standard small wire size is about 3 mm in diameter, which represents a compromise between mechanical strength and electric field and voltage requirements. Larger wires are used to give higher fields when collecting higher resistivity dust. However, as noted in Section 1.1, increasing the wire diameter decreases the field at the electrode while maintaining a higher field overall. Pontius, Vann Bush and Sparks (1984) reported results from a large pilot-scale study that showed a four-fold decrease in particle penetration for large (9 mm diameter) wires over small (3 mm diameter) wires, for a high-resistivity dust. They concluded that each precipitator should be designed for the particular restraints on performance (such as high resistivity dust) and that significant benefits may result from using large diameter wires. One solution is to use a two-stage precipitator in which the particles are charged in a high current inlet section and collected in a high-field section (Oglesby and Nichols, 1978). The separation of the two operations of an ESP, particle charging and collection, allows for the optimization of design for each function. The cold-pipe precharger is quite promising. In this section, discharge electrodes are interspersed with grounded pipes carrying cooling water. As a dust layer forms on the pipes, it is cooled and the resistivity decreased to allow the use of high field strengths which give the particles high charge levels (Plaks, 1984).

2.5.2 Wire-to-Wire Spacing

The inter-wire spacing depends on the wire-to-plate spacing. For a wire-to-plate spacing of 250 mm, the optimum interwire spacing is about 20-25 cm (Oglesby and Nichols, 1978). If the wires are too close together, there is interference between the field lines of adjacent wires. If the spacing is too great the plate area is underused and there are spaces of suboptimal current between the wires.

2.5.3 Wire-to-Plate Spacing

Wide plate spacing (450 mm as compared to standard 230 mm) can result in capital cost savings of up to 20%, and the reduction in electrode plates and rapper systems should significantly reduce maintenance costs (Makansi, 1986). As the spacing increases the applied voltage must increase to maintain the average field across the space. The larger space charge contained in this larger space causes the field at the plate to be increased for a given current. Therefore, the migration velocity in the Deutsch equation, equation 9, increases, and the collection efficiency is maintained as the specific collection area is decreased.

2.6 Rapping and Reentrainment

The Deutsch equation only predicts the deposition of dust on collecting electrodes. Once deposited it must be transferred to hoppers, which results in reentrainment of particles into the gas stream. Therefore the overall efficiency of the precipitator will always be less than that predicted by the Deutsch equation.

Collecting plate electrodes are rapped or shaken to dislodge dust accumulations when the thickness of the layer is about 6-19 mm. The force applied to the plates must be at least 10-25 times the force of gravity (Katz, 1984). At the same time, the lowest rapping intensity required to dislodge the dust should be employed to avoid breaking the dust cake and projecting the particles into the gas flow.

Rapping cycle times vary throughout the precipitator according to the rate of accumulation of dust in different precipitator sections. If the buildup is too small when rapping occurs, agglomerates will not fall into the hopper but will instead become reentrained. If it is too thick, problems related to dust resistivity will be encountered. Diverting the gas flow during rapping increases the collection efficiency (Strauss, 1975).

3.0 PARTICULATE RESISTIVITY

3.1 Effects on Performance

The resistivity of the dust has a significant effect on precipitator performance.

Particles arriving at the collecting electrode surface partially discharge and adhere to the electrode, or to previously captured particles, by three types of forces - molecular adhesive forces, surface tension if there is moisture present, and electrostatic forces. When the dust resistivity is very low (eg, carbon black at 10^{-5} Ωm) the particles are reentrained on contact with the collecting electrode and the collecting efficiency is very low. When the dust resistivity is high the collected particles discharge slowly and a charge builds up in the collected layer. The incoming charged dust represents a current of about 0.1 to 0.5 mA/m^2 which must pass through the collected dust layer (Matts, 1986). Ohm's law (V = IR) gives the strength of the electric field across the dust layer with resistance R. This resistance is related to the resistivity, ρ, by

$$R = \rho \frac{x}{A}$$

where x is the thickness of the dust layer and A the cross sectional area. So, if $\frac{I\rho}{A}$ remains constant, the voltage drop increases with the thickness of the layer of deposited particles. The force holding the dust to the electrode hinders the cleaning which, in turn, interferes with the current supply, and reduces precipitator collection efficiency.

A very high voltage drop across the dust layer can lead to electrical breakdown of the gas in the interstitial space of the dust layer. This causes a corona-like discharge from the dust layer producing positive and negative ions. The positive ions neutralize incoming negative ions and reduce the particle collection rate. If the dust layer resistivity is moderately high (10^8 - 10^9 Ωm), sparking may occur between the two electrodes. The higher the resistivity, the lower the current density must be kept to keep the precipitator functioning without excessive sparking, or back-corona. This can seriously reduce the collection efficiency of the precipitator.

3.2 Composition Effects

At high temperatures, (greater than about 225°C) conduction occurs through the particulate mass in what is termed volume conduction. The composition of the dust is very significant,

but the composition of the flue gas is unimportant. Electrical current is conducted via sodium and lithium ions, and the resistivity is inversely proportional to the atom per cent of these elements in the flyash. Iron plays a role in conduction but is not a current carrier (Bickelhaupt, 1975).

Surface conduction also occurs via metallic ion migration but it occurs in the moisture film surrounding the flyash particles. Oglesby and Nichols (1978) suggest that the presence of SO_3 reduces resistivity significantly because it attacks the ash surface and causes the release of ionic charge carriers. Yung et al (1985) suggest that the SO_3 forms on aqueous sulphuric acid film on flyash particles, which, being very conductive, conducts the charge itself.

3.3 Temperature, and Humidity Effects

The resistivities of flyash and of limestone are strong functions of temperature and humidity. At temperatures below 90°C, a high moisture content lowers the resistivity because conduction occurs in the condensed film around the particles. The resistivity reaches a maximum between 90°C and 180°C, then begins to decrease as the temperature rises and conduction through the particles increases. Beyond 250°C-300°C, the effect of moisture is negligible (Strauss, 1975). Sulfur in powdered form is an exception and remains a perfect insulator, due, in part, to its hydrophobic nature.

Ogawa (1985) gives the optimal dust resistivity for capture by an ESP as 10^2-10^9 Ωm. Experimentally determined resistivities for flyash are presented that show a decrease from 5×10^{10} to 10^6 Ωm as the relative humidity increases from 10% to 92%.

Particle size influences the bulk resistivity because smaller particles form a dust layer with smaller voids than those found in dust layers of larger particles. Resistivity decreases with decreasing void space. Also, smaller particles have a greater specific surface area on which a conducting water film may form. Particle size, in practice, is usually related to composition and this may have a greater influence on resistivity than size, as shown by Ogawa (1985).

3.4 Resistivity Modifications

Resistivity is a function of temperature, so, one approach to altering the resistivity would be to increase or decrease the temperature. Increasing the temperature has attendant problems such as increased flue gas volume and increased gas viscosity. Lowering the temperature can lead to corrosion or fouling problems.

Water conditioning is an excellent method of improving dust resistivity characteristics, but the ESP inlet temperatures are usually too low to evaporate a sufficient quantity of water causing corrosion and fouling problems. Steam injection provides good moisture conditioning but the cost is prohibitive.

Yung et al (1985) conducted a survey of available flue gas conditioning agents and user experience. Sulphur trioxide is the most widely used. It will give improved ESP performance if resistivity is the limiting factor. The drawbacks to using SO_3 to lower resistivity are the costs involved, including those for handling, temperature and moisture control and safety.

Naturally generated SO_3 produced from SO_2-bearing coal in the boiler enters the ESP in the form of sulphuric acid aerosol (Gomoll, 1984). For conditioning to occur, these aerosols must contact flyash particles. However, given the small sizes and electronegative surface properties, this does not occur readily. SO_3 conditioning has a greater effect because the gaseous SO_3 contacts the water film on the very fine particles and forms sulphuric acid on the particles themselves, lowering the resistivity by up to three orders of magnitude. The quantities that can be injected without increasing SO_3 outlet concentrations depend on the flyash. A basic ash allows higher SO_3 concentrations but requires higher injection rates to achieve the necessary reductions in flyash resistivity.

3.5 Combined Strategies

In many cases, a combination of collection enhancement methods will be required.

In a pilot-scale (0.3 MW) study, Abbott et al (1985) found that furnace injection of crushed limestone produces high resistivity flyash/sorbent particulate matter in the absence of SO_3. The flyash without sorbent had a measured resistivity of 2×10^8 Ωm. Flyash/sorbent particulate matter had a resistivity of 2×10^{10} Ωm without SO_3 conditioning and 2×10^8 Ωm with 5 ppm SO_3 and 8% water vapor at 150°C. The increased loading to the precipitator due to the 2:1 Ca:S injection requires further precipitator modification to bring the outlet mass loading down to an acceptable level. They found that this could be accomplished by adding a precharging section with conventional electrode geometry followed by three collecting sections with discharge electrode wires of one centimetre diameter.

3.6 Pulsed Energization

The problem of collecting high resistivity dust may be solved through the use of pulse energization of the precipitator. Alternating a high current for a few microseconds with nc

current for a few milliseconds prevents back-corona from developing. The dust layer acts like a leaky capacitor with a time constant in the order of seconds. During the high current pulse, the current distribution along the discharge electrode is good, and as the particles travel, on average, less than 1.5 cm between pulses, no dust escapes uncharged (Matts, 1986).

A comprehensive literature review on pulse energization by Corbin (1984) concludes that there are many benefits to pulse energizing, including enhanced control of the precipitator under back-corona conditions with high-resistivity dusts. Porle and Matsui (1984) reported that power savings due to pulsing might be as important a benefit as the improvement in the efficiency.

4.0 CONCLUSIONS AND RECOMMENDATIONS

In general, dry SO_2 reduction strategies will involve switching to a low sulfur coal and/or injection of a lime or limestone sorbent in solid or slurry form, either into the boiler or between the boiler and the ESP. Either choice will produce larger volumes of higher resistivity dust than is currently the case. The electrostatic precipitators now in use were not designed to remove the products of these proposed SO_2 reduction methods, and, in the future, the ESPs will have to be upgraded or replaced.

One promising SO_2 reduction/flyash collection method has a lime spray dryer and baghouse combination. The advantages of this system include additional SO_2 removal by the filter cake over that of the spray dryer alone, and high dust removal efficiency.

Ontario Hydro, however, will probably be better served by modifications of the existing electrostatic precipitators to deal with the large volumes of flyash/sorbent. Actual field studies will have to be conducted to determine if SO_3 conditioning, along with ESP modifications such as pulse energization or the addition of a cold-pipe precharger, can be used to meet emission requirements. If not, two alternative approaches can be tried. The first is the addition of a mechanical precleaner such as a cyclone, to remove the 60-70% of the dust that is larger than 10 μm. The second approach is to place additional collectors, such as another precipitator bank or a baghouse, after the existing ESPs. Detailed field studies and economic analyses will be required before specific recommendations are possible.

Further information on ESP upgrading can be found in the following Proceedings.

EPA/EPRI CS-4404, V1-4, Symp. on the Transfer and Utilization of Particulate Control Technology (5th) 1984.

EPA/EPRI CS-4918 V1-3, Symp. on the Transfer and Utilization of Particulate Control Technology (6th) 1986.

Approved by:

M.R. Booth
Acting Manager
Chemical Research Department

WM/mf

Prepared by:

W. Mortimer
Chemist
Environmental Science Section

Reviewed by:

O.T. Melo
Supervising Engineer
Environmental Science Section

REFERENCES

Abbott, J.H., J.P. Gooch and J.D. Kilgroe, 1984 "Proceedings of the Second International Conference on Electrostatic Precipitation," Kyoto, APCA, Pittsburgh.

Bickelhaupt, R.E., 1975. Environmental Science and Technology 9(4): 336-342.

Cooperman, G., 1984. Atmospheric Environment 18(2): 277-285.

Corbin, R.G., 1984 "Proceedings of the Second International Conference on Electrostatic Precipitation," Kyoto, APCA, Pittsburgh.

Gomoll, H.-J., 1984 "Proceedings of the Second International Conference on Electrostatic Precipitation," Kyoto, APCA, Pittsburgh.

Makansi, J., 1986. "Power; A Special Report," (12) S1-S16.

Matts, S., 1986. "Flakt Electrostatic Precipitator" - Promotional Literature.

Ogawa, 1985. "Separation of Particles from Air and Gases".

Oglesby, S. and G.B. Nichols, 1978. "Electrostatic Precipitation", Marcel Dekker, Inc. NY.

Plaks, K., 1984 "Proceedings of the Second International Conference on Electrostatic Precipitation," Kyoto, APCA, Pittsburgh.

Pontius, D.H., P. Vann Bush and L.E. Sparks, 1984. JAPCA 34: 1203-1207.

Porle, K., and Y. Matsui, 1984 "Proceedings of the Second International Conference on Electrostatic Precipitation," Kyoto, APCA, Pittsburgh.

Strauss, W., 1975. "Industrial Gas Cleaning", Pergamon Press, Oxford.

Vann Bush, P., 1984. Environ. Sci. Technol. 18(9): 699-705.

Yung, S-C., R.G. Patterson, B.L. Hancock and S. Calvert, 1985. EPA/600/7-85/005.

DISTRIBUTION

Dr. D. Mills	Director of Research
Mr. C.W. Dawson	Design & Dev - Gen, H10D01
Mr. C.J. Barnett	Design & Dev - Gen, H13A09
Mr. Y.-W. Jao	Lakeview TGS
Mr. D.J. Dodd	Chemical Research
Dr. M. Mozes	Chemical Research
Dr. Y.V. Nguyen	Chemical Research
Mr. O.T. Melo	Chemical Research
Dr. A. Kalvins	Chemical Research
Dr. W. Mortimer	Chemical Research

Public Reference Centre
Editorial Section (2)
Office Copies (3)
Extra Copies (3)